Deep Submillimeter Imaging of Dust Structures in Centaurus A

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ABSTRACT

Images covering the central $450 \times 100''$ ($\sim 8.0 \times 2.0$ kpc) of NGC 5128 (Centaurus A) obtained using SCUBA at 850 and 450μm with beam sizes of 14.5 and $8''$ respectively, are presented. These data are compared with those obtained at other wavelengths, in particular the optical, mid-infrared, and far-infrared continuum. The sensitive 850 and 450μm images show that the submillimeter (submm) continuum morphology and spectral index distribution of Centaurus A comprise four regions: an unresolved AGN core, an inner jet interacting with gas in the dust lane, an inner disk of radii $\sim 90''$, and colder outer dust. The inner disk has a high surface brightness, reverse-S-shaped feature in the 850 and 450μm images that coincides with the regions of intense 7 and $15\,\mu$m continuum and a region of active star-formation. The infrared (IR) and submm images appear to reveal the same material as predicted by a geometric warped disk model consisting of tilted rings. We suggest this scenario is more plausible than that recently proposed in literature suggesting that the mid-IR emission in Centaurus A is primarily from a bar, with a structure that is different from the extended warped disk alone. A dust mass total of $2.2 \times 10^{6} M_\odot$ has been calculated within a radius of $225''$, 45% of which is in the star-forming region of radius $\sim 90''$ about the nucleus.

Subject headings: dust — galaxies: active — galaxies: individual (Centaurus A, NGC 5128) — galaxies: structure — submillimeter — radiation mechanisms: thermal

1. Introduction

NGC 5128 (Centaurus A), at an assumed distance of ~ 3.5 Mpc (Hui et al. 1993), is the nearest giant elliptical galaxy and is remarkable in several respects. It is a powerful radio source with a double-lobed structure extending approximately $3°.5 \times 8°.5$ on the sky (Bolton, Stanley, & Slee 1949; Clarke et al. 1992; Tingay et al. 1998). At the other extreme of scales a central source, less than 0.4 milliarcsec (~ 0.008 pc) in extent (Kellermann, Zensus, & Cohen 1997), is prominent on radio through X-ray images. This compact object feeds subparsec-scale relativistic outflows that are approximately aligned with, and clearly the generators of, the vast outer radio lobes (e.g. Tingay et al. 1998).

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The optical appearance is dominated by a dramatic warped dust lane at least 12′.5 in E-W extent, which effectively bisects the main body of the elliptical galaxy and almost completely obscures the nucleus and all optical structure in the inner 500 parsecs (e.g. Schreier et al. 1996). The outer isophotes of Centaurus A are markedly elongated in P.A. $\sim 25°$. Faint shells, associated with both H I and CO emission, are evident in these outlying parts (Malin, Quinn, & Graham 1983; Schimonovich et al. 1994; Charmandaris, Combes, & van der Hulst 2000). The somewhat chaotic dust lane, and especially the shells, are strong evidence of a relatively recent merger (Baade & Minkowski 1954; Graham 1979; Tubbs 1980; Schreier et al. 1996; Israel 1998) which is generally believed (c.f. Marconi et al. (2000) and references therein) to be responsible for the nuclear activity. Hα and molecular line observations (e.g. van Gorkom et al. 1990) indicate that the nucleus is surrounded by a rapidly rotating massive inner disk of radius ~ 2 kpc with a pronounced warp (Nicholson, Bland-Hawthorne, & Taylor 1992; Quillen et al. 1992), a scenario that is supported by modelling of the structure of the obscuring dust seen in near-infrared (Quillen, Graham, & Frogel 1993) images.

Submillimetre wavelength emission, apparently thermal in origin, was first observed from Centaurus A by Cunningham et al. (1986), using the single-pixel bolometer UKT14 mounted on the 3.8-m UK Infrared Telescope with a beam size of $\sim 80''$. Millimeter-wave continuum observations by Eckart et al. (1990) in $22''$ and $45''$ beams show an unresolved nuclear source, surrounded by extended thermal emission seen by $IRAS$ at 50 and 100μm and which is roughly co-extensive with a region of strong CO molecular line emission. More extensive submm continuum observations were made by Hawarden et al. (1993), who mapped the galaxy using the smaller beamsize of $\sim 15''$ afforded by UKT14 mounted on the 15-m James Clerk Maxwell Telescope (JCMT).[6] Although ex-

tended emission was visible in their images, these were not sensitive enough to reveal much detailed structure beyond a general extension corresponding to the optical dust lane and a brighter, elongated, central feature, with an apparently thermal spectrum, surrounding the strong, flat-spectrum nuclear source.

This paper presents new high-quality images of Centaurus A obtained at submm wavelengths, that are sensitive in particular to emission from cold interstellar dust. These resolve the structure of the inner disk down to scales of about $8''$ (~ 150 pc), while also revealing details not previously seen of the faint outer dust emission at large radii. Recently, Mirabel et al. (1999) used ISO-CAM, the infrared (IR) imager on the *Infrared Space Observatory* (ISO),[7] to obtain images at mid-IR wavelengths, and these results are compared, together with observations at other wavelengths, with those presented in this paper. Reprocessed $IRAS$[8] data are also presented to complement the detailed study of the dust properties in the disk.

2. Observations

Centaurus A presents special challenges for observations at submm wavelength from Mauna Kea since it never rises more than $28°$ above the southern horizon. Images were nevertheless obtained using the submm wavelength bolometer array SCUBA (Holland et al. 1999) during several observing periods with the JCMT during 1998.

The simultaneous 850 and 450μm images were obtained during three nights (UT 1998 March 29, April 9 and April 11) during a period in which sky conditions were exceptionally transparent, with zenith opacities often as low as 0.1 and 0.4 or better at 850 and 450μm respectively. The data were taken using the "jiggle-mapping" mode of

SCUBA, which provides a densely-oversampled image with a spacing of 2″.18, and each observation results in a field about 2′.3 in diameter. The array orientation rotates with respect to the sky as the observation progresses, further sampling the image plane. A series of seven overlapping field centers were observed, placed 55″ apart along a line at a position angle of 120° (North through East), roughly corresponding to that of the dust lane of Centaurus A. The chop throw was 120″ perpendicular to this line.

The strong overlap (more than 50%) between neighboring fields compensated for the limited rotation of Centaurus A with respect to the SCUBA arrays, offsetting the effect on the final reduced images of occasional excessively noisy pixels. A different subset of the seven fields was observed on each of the three nights. Since the bright nuclear source appears on the central three fields, it was observed at least twice per night, which allowed corrections for pointing drifts to be measured and applied to the final images.

To determine the beam pattern of the JCMT, the bright unresolved blazar 3C 279 was observed each night using the same jiggle-pattern mode as applied to Centaurus A. Atmospheric opacities were determined from skydips made at intervals during the observing, and instrumental gains were derived from images of the JCMT secondary calibrators CRL 618, IRC+10216 and IRAS 16293−2422 (Sandell 1994, 1998). The imaging data analysis was undertaken using the dedicated SCUBA data reduction software SURF (Jenness, Lightfoot, & Holland 1998), as well as KAPPA, GAIA and CONVERT software packages provided by the Starlink Project[9]. The data reduction consisted of first flatfielding the array images, and then correcting for atmospheric extinction. Next, pixels significantly noisier than the mean were blanked-out; and, after initial inspection of raw images, pixels containing relatively little flux from the source were used to correct for correlated sky noise in each individual jiggle-map. Corrections for pointing drifts were incorporated in the final images using the fields in which the

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[9]The Starlink Project is run by the Council for the Central Laboratory of the Research Councils on behalf of the Particle Physics and Astronomy Research Council of the United Kingdom.

core source appeared. The apparent core source size was reduced from 9.24 to 8″.42 (FWHM) at 450μm after the inclusion of these corrections.

An image at 850μm had been previously obtained under somewhat worse conditions on UT 1998 February 14, 15 and 16. This image was made using the "scan-mapping" mode and covers an area 4′ square centered on the bright core source. Despite the lower quality of this dataset, it provides a useful comparison dataset for the reality of features in the two 850μm images. The sky transmission was not good enough on this occasion for the simultaneous 450μm data to be useful. The instrumental gains for the "scan-mapping" mode observations are 20% less than those typical for the "jiggle-mapping" mode; therefore, the gains have to be determined separately for the individual modes. The beam in the 850μm "scan-mapping" image of Centaurus A in this paper is slightly larger than in the "jiggle-mapping" images and the photometry differences between the two final maps are within and proportional to the uncertainties: the percentage differences are larger in the less sensitive parts of the maps.

3. Results and Discussion

3.1. The Submm Images and Comparisons with other Wavelengths

The images of Centaurus A at 850 and 450μm obtained from the combined "jiggle-map" datasets are about 6′ long and 2′ wide (respectively 7 kpc and 1.7 kpc at Centaurus A) and cover much of the dust disk. The 850 and 450μm maps, which respectively have rms noise values of 5 and 20 mJy/beam, are shown in Figure 1. Figure 2 shows the $850\,\mu$m image obtained from the "scan-mapping" observations, which has an rms noise of 25 mJy/beam.

The submm images show extended emission centered on the nucleus of Centaurus A and oriented at a position angle of about 115° (North through East) on the plane of the sky, in roughly the same orientation as the prominent optical dust lane. Within about 90″ at both 850 and 450μm, the emission has a much higher surface brightness than at larger radii. The bright structures have a reversed S-shape suggestive of spiral structure or, as proposed by Mirabel et al. (1999), a bar.

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The central source has a flux density per beam at least 40 times brighter than the surrounding emission from the dust lane, as shown in the profiles along the major axis in Figure 3. Furthermore, the close resemblance of the central source to the profiles of the JCMT beam (line with crosses in Figure 3), shows the source is unresolved. The point-source core has been isolated from the extended emission and separate submm-to-IR spectral energy distributions (hereafter SED) have been constructed for the core and extended galactic emission. These are discussed in Section 3.3.

Figure 4 shows the 450μm contours, our highest resolution new SCUBA image, superimposed on a) an optical waveband (395 and 540 nm) image courtesy of the Anglo-Australian Observatory[10] and b) the ISOCAM 7μm image. We now discuss these comparisons, as well as what we learn from the $450/850\mu$m spectral index distribution map, in more detail.

3.1.1. Submm vs. Optical Morphology

The well-defined reverse-S-shape structure seen in high surface brightness submm emission, within $90''$ of the galaxy nucleus, is largely indiscernible in optical maps, implying that the denser material around the nucleus, seen in the submm-wavelength images is heavily obscured at optical wavelengths. However, the southern edge of the SE high surface brightness submm emission aligns with the southern ridge of the optical dust lane, in turn suggesting that the SE reverse-S-shape structure is on the near-side and therefore relatively less obscured in the optical, as reported by Block & Sauvage (2000) and Quillen, Graham, & Frogel (1993) and based on their analyses of mid-infrared versus V and near-infrared data respectively. Furthermore, if the submm/optical morphology is a manifestation of a warped dusty disk or spiral structure that is highly inclined to the plane of the sky (c.f. Section 3.2), the southern edge is consistent with an inner fold of the disk seen tangent to the line of sight. Such a ridge would have a high column den-

sity in the line of sight, as evident in the aligned southern edges of *high* surface brightness submm emission and the *dark* optical lane.

A very rough estimate can be made of the optical depths detected in the SCUBA images, allowing a quantitative comparison between the submm emission and optical obscuration. Using the emissivity (i.e. grain absorption coefficient) from Hildebrand (1983) and assuming a grain temperature of 17 K (c.f. the diffuse dust in the Galaxy), a V-band optical depth of about 10 can be inferred for a surface brightness of ~ 30 mJy/beam at 850μm, as seen in the low-level emission detected in the current submm images. Dust clouds that are evident in the optical image presented in this paper are expected to have V-band optical depths of ~ 10. Therefore, under reasonable assumptions, the dust lanes seen in the optical obscuration map exhibited here should be detected in the SCUBA images.

Figure 4 shows that the low surface brightness submm emission generally follows the optical dust absorption distribution, including the clockwise twists in the east and west of the dust lane. This submm emission corresponds especially well with the dark optical obscuration in the NW and northern part of the SE dust lanes, and also with the very dark twist in the east, indicating that some low level submm emission must arise from the optically prominent dust material. There is no marked difference between the flux densities of submm low level emission that corresponds with the dark optical obscuration in the northern edge of the SE dust lane and the low level emission in the southern ridge of the dust lane: in both regions, the flux densities are in the range ~ 40 to ~ 120 mJy/beam and ~ 10 to ~ 60 mJy/beam at 450μm and 850μm respectively. Schreier et al. (1996) find that the extinction along the southern ridge is much more than that in the northern edge of the SE dust lane, where it reduces the R flux by a factor of 6 compared to a factor of only 1.5 to 2 in the northern edge of the SE lane. Therefore, the similarity of the flux densities in the northern and southern low level submm emission despite the higher extinction in the southern ridge indicates that the northern edge of the SE dust lane is well in the foreground, in a region of low stellar density, and is thus heated by a more dilute stellar radiation field.

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Within the length (major diameter) of $270''$ that excludes the clockwise twists, low surface brightness submm emission extends farther north and south beyond the optical feature: the average width (minor diameter) of the dust feature seen in submm emission is $> \sim 90''$ compared with the optical obscuration of $\sim < 60''$ (see Figure 4(a)). The extension is appreciably marked in the south, where the dust giving rise to the submm emission here lies on the far-side of the galaxy and is overlain by the stellar body. Consistent with this scenario, when Schreier et al. (1996) removed the effects of foreground dust obscuration from HST I' band images, they found a band of residual obscuration, presumably caused by dust within the stars on the farther side of the galaxy.

While it is clear that the maximum width at which the dust lane will be detected in extinction and seen in thermal emission will depend on the relative sensitivity of the two techniques, the width at which the feature is detected in the submm observations ($> \sim 90''$, c.f. Figure 4(a)) surpasses the maximum width detected in all optical observations we are currently aware of, including the recent HST (Schreier et al. 1996; Marconi et al. 2000) and VLT[11] observations ($\sim < 60''$), supporting the assertion that the low-level submm emission extends well beyond the optical obscuration.

3.1.2.   Submm vs. ISO Mid-IR Morphology

Mirabel et al. (1999) presented images of Centaurus A at 7 and 15μm obtained with ISO-CAM as well as early SCUBA "jiggle-mapping" images of a $2'$ field around the core of the galaxy at 450 and 850μm. They note the similarity of their IR (ISOCAM) and submm (SCUBA) images (which are much less sensitive to faint emission than those presented here), observing that there was the "same general distribution" between the "warm" and "cold" dust seen respectively in the ISOCAM and the early SCUBA image published by them. Mirabel et al. (1999) conclude that the absence of submm emission from the optical dark lanes "is not due to major differences between the spatial distributions of the cold and very warm

dust components," attributing the optical dust features to "small amounts of cold dust in the outer parts" of the system.

The SCUBA data exhibited in this paper, which have much greater sensitivity and extend much farther from the nucleus than the images published by Mirabel et al. (1999), show that there are *remarkable* similarities between the appearance of Centaurus A in the mid-IR and the submm (see Figure 1, Figure 4(b)). This is particularly true of the 450 and 7μm images, even though their wavelengths differ by a factor of 65. Both images show the reverse-S-shaped, high surface brightness structure out to $90''$ from the core and the fainter extensions of this structure out to $120''$. The major *difference* is that the submm emission is seen to much larger angular distances than is the mid-IR, and as pointed out above, faint submm emission from some of the more outlying dust in the optical dust lane is evident.

The contours in Figure 4(b) show a feature extending to about $15''$ radius from the nucleus in position angle $145°$; this may correspond to that attributed to a circumnuclear torus by Hawarden et al. (1993); Israel (1998) and Bryant & Hunstead (1999). The SCUBA and ISOCAM images suggest it may represent the inner folds of the reverse-S-shaped structure (or warped disk, c.f. Section 3.2) mentioned above.

3.1.3.   The Spectral Index Distribution

Using the 450 and 850μm imaging data, the global spectral index distribution of Centaurus A is derived at submm wavelengths and used to delineate the submm components in the nuclear regions of the galaxy as well as to investigate the dust properties of the extended emission. The following procedure was used. The 450μm data were first smoothed to the $14''$ resolution of the 850μm map. The spectral index α, where $S_\nu \propto \nu^\alpha$, between 450μm and 850μm was then computed as

$$\alpha = \log\left[\frac{S_{450}}{S_{850}}\right] \Big/ \log\left[\frac{850}{450}\right], \qquad (1)$$

where S is the flux density per beam at each point in the map. The uncertainty in the spectral index

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[11]VLT astronomical image gallery is available at http://www.eso.org/outreach/info-events/ut1fl/astroimages.html

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is then given by

$$(\Delta\alpha)^2 = \left[\left(\frac{\Delta S_{450}}{S_{450}}\right)^2 + \left(\frac{\Delta S_{850}}{S_{850}}\right)^2\right] \bigg/ \left(\log\frac{850}{450}\right)^2,$$

$$(2)$$

where the variables are as for equation 1. The largest probable uncertainty in ΔS arises from the calibration, especially for the 450μm flux densities. The maximum uncertainty in our final map is estimated as $\mid\Delta\alpha\mid_{\mathrm{max}} \approx 1.5$ and the mean uncertainty as $\mid\Delta\alpha\mid_{\mathrm{mean}} \approx 0.5$. The uncertainty in the regions with $\alpha > 3.2$ is most probably underestimated as this is also the region of the map with the least sensitivity.

The spectral index map of Centaurus A between 450 and 850μm is shown in Figure 5. There are four regions apparent in the map. Contours at the spectral indices 2.0 (dashed lines) and 3.0 and 3.3 (solid lines) are overlaid to guide the eye to the less obviously manifested features. In the nuclear area, the unresolved core and a feature apparently representing the inner jet are distinguished. Farther from the nucleus we can discern, with progressively increasing spectral indices, the bright, reverse-S-shaped structure, familiar from the intensity maps, and the fainter outer dust, roughly corresponding to the optical dust lane (see Section 3.1.1).

The spectral index of the **unresolved core** is close to zero, consistent with the nonthermal spectrum from an AGN nucleus. This paper confirms that the core source has a flat submm spectrum (i.e. $\alpha \approx 0$), which is common for BL Lacs (blazars) (e.g. Brown et al. 1989), and as Hawarden et al. (1993) and Kellermann, Zensus, & Cohen (1997) have noted, suggests that Centaurus A may harbor a low-luminosity blazar.

The feature which this paper refers to as the **inner jet** is not evident on the intensity maps but is prominent in Figure 5 as (green-blue) areas of low spectral index to the NE and SW of the nucleus. The spectral index of these features is in the range $1.5 \leq \alpha \leq 2.5$ (see dashed contour lines). The northern extension is coincident with the inner radio jet (Clarke et al. 1992), which, as implied by the designation in this paper, is not considered to be merely by chance. However, the observed spectral index is much higher than would be expected from extrapolation of the power-law spectrum of the radio jet itself. One possible ex-

planation is that the submm spectrum is not a manifestation of the electron distribution of the relativistic radio jet itself (or the jet overlaid by a warm dust component), but rather of some internal mechanism (e.g. ionization of gas) resulting from the interaction of the jet and the ISM in the inner regions of the galaxy.

Brodie, Konigl, & Bowyer (1983) and others have proposed that optical jets in galaxies such as Centaurus A may be due to emission from interstellar gas that has been entrained and heated by the flow of relativistic particles from the nucleus. The entrained gas would generate free-free continuum emission with spectral index, in the optically thick case, of $\alpha \approx 2$, consistent with the observed spectral range of the inner jet $1.5 \leq \alpha \leq 2.5$. We attribute the southern nuclear extension in our submm spectral map to the same mechanism, though in this case associated with the fainter counter jet recently reported by Tingay et al. (1998) and Kraft et al. (2000), respectively from their high resolution VLBI radio and *Chandra* X-ray images.

A similar interaction of the jet and interstellar medium was proposed by Joy et al. (1991) based on their near-IR observation of the inner jet of Centaurus A, which manifested itself as a region of bluer color, with spectral index $1.3 \leq \alpha \leq 2.9$, coincident with the radio jet. Marconi et al. (2000) also reported a 'blue channel' coincident with the radio jet, but they attributed it to low extinction resulting from relatively low concentration of dust that has been mechanically 'evacuated' by the jet. This paper disagrees with this interpretation as there is no sign of a deficiency of emission on the 450μm map at this location: the inner jet feature of Figure 5 arises from a relative enhancement of emission at 850μm in these locations.

The spectral index of the **inner disk** is in the range $2.5 \leq \alpha \leq 3.2$, consistent with thermal emission from dust. The lowest indices occur in an almost circular region about $30''$ in radius around the nucleus; this is coincident with an area of hot molecular gas reported by Schreier et al. (1998)[12] from their *HST* observations. Emission with a steeper spectrum ($2.6 \leq \alpha \leq 3.2$, see solid con-

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[12]STScI-PRC98-14 Electronic Press Release is available at http://oposite.stsci.edu/pubinfo/pr/1998/14/pr-photos.html

tour lines) approximately traces the inner disk of brighter structures seen in the 7 and 450μm images (see Section 3.1.2 and Figure 4b) out to $\sim 90''$. Farther still from the nucleus, in the fainter **outer disk** the spectral index increases to $\alpha \sim 4$. As underscored by the solid line contours in Figure 5, the spectral index is asymmetric about the nucleus in the inner disk region of the map: it is somewhat flatter on the eastern part of the inner disk, indicating slightly different relative distributions of dust grains on either side of the nucleus.

If the dust seen in the maps presented in this paper is emitting with spectral index $\alpha = 2 + \beta$ (where β is the emissivity index), the spectral index in the extended region implies that for a given temperature, the dust in Centaurus A has on average a low β., i.e. the dust is made of relatively large grains, and that its temperature is fairly cool. Furthermore, the somewhat flatter spectral index in the south-east suggests the dust in this region is made of smaller grains with moderately warmer temperatures than those in the same region in the NW. This is not surprising as the SE is reported to exhibit stronger H I emission (van Gorkom et al. 1990), weaker $^{12}CO(1$-$0)$ and stronger H α line emission compared to the NW, that led Eckart et al. (1990) to speculate that star-formation and its associated high radiation field were greater in the SE.

The uncertainty in the emissivity analysis in our spectral index map (Figure 5) does not permit us to quantitatively examine the effects, if any, due to diffuse "cirrus" grains in the map. The dust in the outer disk, where the emissivity index $\beta > 1.5$, may well consist of "cirrus" grains, which, as it is generally accepted (e.g. Rowan-Robinson 1992), would have an emissivity index close to $\beta = 2$ and temperatures $15 < T < 40\,\mathrm{K}$. Eckart et al. (1990) associated the far-IR emission outside the molecular star-forming disk (ie. radius $>\sim 90''$) with "cirrus" clouds with scale height larger than that of the molecular gas disk. They predicted that the submm extended emission would also originate from dust constituting "cirrus" grains as could well be the case. The large western and eastern warps seen in the 850μm and 450μm images (see Figure 1) resemble the distribution of the H I emission (Schimonovich et al. 1994), indicating that, if the dust in the warp features (and the general outer disk) in Centaurus A

is composed of "cirrus" grains, the H I emission traces the "cirrus" dust in NGC 5128 just as in the Milky Way.

3.2. Implications of the Multiwavelength Images

Our submm images demonstrate that outlying dust in Centaurus A is significantly cooler than the material in the bright elongated features within $\sim 90''$ of the nucleus. This is naturally to be expected: at larger radii the ambient radiation field heating the dust is more dilute because of the much lower density of stars (Eckart et al. 1990; Schreier et al. 1996; Marconi et al. 2000). The emission from this dust generally follows the optical dust lane.

The warped disk model proposed by (Quillen et al. 1992) and explored by Quillen, Graham, & Frogel (1993), consisting of tilted rings of material, predicts the structure of such warmer and colder material, respectively seen in the mid-IR and far-IR to submm, rather well. This scenario is supported by Eckart, Wild, & Ageorges (1999), who showed that a warped structure of tilted rings explained not only the line emission in the disk of Centaurus A (Quillen, Graham, & Frogel 1993), but also a complex absorption-line system towards the nucleus, without a need for any additional structures.

From their *ISO* 7 and 15μm images, Mirabel et al. (1999) conclude from a comparison with similar mid-IR images of the dwarf barred spiral NGC 1530 that the structure imaged in the mid-IR in Centaurus A is itself a barred spiral: the prominent emission peaks $\sim 75''$ from the nucleus at each end of the bright mid-IR and submm structures are hypothesised to be foreshortened arms twisting anti-clockwise from the outer ends of the bar. Block & Sauvage (2000) support this proposal from their VHK and 15μm study of Centaurus A, noting too that the warm dust seen by ISOCAM contributes little to the extinction seen at optical wavelengths.

Kinematics is clearly important in understanding the true nature of the near-nuclear structures in Centaurus A. Mirabel et al. (1999) address these in their Figure 4, a comparison of the IR images with the CO kinematics in the form of a position-velocity (P-V) plot from Quillen et al.

(1992). On this figure they identify the strong CO feature extending from $-1'.2, 300\,\mathrm{km\,s^{-1}}$ to $+1'.2, 800\,\mathrm{km\,s^{-1}}$ as the bar, undergoing solid body rotation, and weaker outlying features at nearly constant velocity at larger radii as the "typical" rotation curve of galactic disks.

However, an alternative interpretation of the PV diagram is that the "bar" represents a nearly-complete, highly foreshortened, ring of material at a radius of $\sim 65''$ ($\sim 1300\,\mathrm{pc}$). In that scenario the concentrations of IR and submm emission NW and SE of the nucleus represent the ends of the ring where the optical depth is maximized. Similarly, the "EW high-velocity feature" mentioned by Mirabel et al. (1999), which they note does not fit their scenario, is readily explained by another ring of molecular material at a radius of $\sim 20''$ ($\sim 400\,\mathrm{pc}$), tilted relative to the outer ring and evident on the mid-IR images as two small extensions to the nuclear feature in PA 80° and 260°. Furthermore, the outer features of the PV diagram also have an alternative interpretation: the feature $>1'.7$SE of the nucleus has the properties of an arc of material starting at radius of $\sim 4.6\,\mathrm{kpc}$ and ending perhaps 2 kpc from the nucleus close to the minor axis: in an normal edge-on spiral, such a feature would be interpreted as a spiral arm.

Marconi et al. (2000) also accept the bar model since its edges appear to be delineated by linear concentrations of star-forming regions seen in their Pa α images, suggesting that these delineate the shocks normally seen as dust lanes along the leading edges or the midlines of galaxy bars in optical images. However, they also noted that their data do not rule out a warped ring without a bar, as the star-formation is found in regions of the warp that are tangent to the line of sight, and if the young stars are above or inside the disk, they would indeed appear to be concentrated where the Pa α emission is seen.

We suggest the latter interpretation is more plausible for the following two reasons. First, the same elongated distribution of Pa α emission regions, which Marconi et al. (2000) show to coincide precisely with the elongated mid-IR ridge that passes just south of the nucleus, is equally coincident with the dense, narrow, optical dust lane that passes south of the nucleus in Figure 4(a). Since this is the *only* feature of the bright central complex (apart from the nucleus itself) that is potentially identifiable with an optically-visible feature, we suggest that it is not in fact part of the near-nuclear complex at all, but, as suggested by the models of Quillen et al. (1992), a manifestation of an outlying fold or ring in the warped disk.

Second, we note that the bar-shocks traced by dust in early-type field spirals are asymmetric about their nuclei, since they lie in the leading edges of the bars, while those in late type systems are centered in the bars. However, the Pa α emission regions in Figure 13 of Marconi et al. (2000) pass by several arcsecs south of the nucleus from the SE to west of the nucleus. This is not what would be expected of a shock in a bar in a field spiral, but more the distribution to be expected if the star-forming regions are associated with the trailing dust lanes in a typical spiral arm, or in this case the dusty rings postulated by Quillen et al. (1992).

Therefore, the combined evidence to date from the CO kinematics, the mid-IR images, the bright and faint submm features and the Pa α images supports the warped rings model of Quillen et al. (1992) rather than indicating the presence of a true bar, and may even represent spiral structure in the dust lane of Centaurus A.

One of the attractions of the bar scenario for both Mirabel et al. (1999) and Marconi et al. (2000) is its expected utility as a mover of material from larger to smaller radii in the disk in order to fuel the AGN. However, since the association of barred structure with the presence of an active nucleus in field galaxies, though long sought, is marginal at best (c.f., for example, Ho, Fillipenko, & Sargent (1996) and references therein), the presence of the AGN cannot be taken as an argument for the reality of the putative bar. Not having a bar to fuel the active nucleus is not too great a loss; e.g. recent work by Duschl, Strittmatter, & Biermann (2000) suggests that viscosity in a thin gas plane may also provide an efficient AGN fuelling mechanism.

3.3. The Extended Emission Temperature and Dust Mass Estimates

This paper has shown that the central source in Centaurus A is unresolved and has a flux density per beam at least 40 times brighter and a spec-

trum markedly flatter than the surrounding emission from the dust lane; i.e. the central source is clearly distinct from the extended emission (c.f. Sections 3 & 3.1.3 and Figure 3 & Figure 5). Therefore, an analysis of the SED for the extended submm to infrared emission in this paper is preceded by the isolation of the point-source core from the extended emission and the determination of the respective flux density estimates for these separate components. Adjustments are made when dealing with the JCMT and ISO data, both taken with small beams, and the $IRAS$ data, which were obtained with significantly larger beams.

The core flux densities from 850 to 7μm are presented in Table 1, together with integrated flux densities determined for two regions of the extended emission from the dust lane: (1) an ellipse of $60 \times 180''$ $minus$ the core measurement and (2) an elliptical annulus of $120 - 60 \times 450 - 180''$. The far-IR flux densities are archival $IRAS$ data for Centaurus A that we re-analysed using the HIRES facility to extract the best possible spatial resolution and to ensure that we have the same registration of the regions from which we determine integrated flux densities. The ellipse and annulus are denoted respectively as the $inner$ $disk$ and $outer$ $disk$, as the two regions have different submm continuum morphology and spectral index distributions (see Sections 3.1.2 & 3.1.3). The SED for the two extended regions are plotted in Figure 6, and temperatures as well as dust masses determined for the emission from these regions are discussed below.

The compact core is unresolved on the submm and ISO mid-IR images (FWHM $< 8''$ at 450μm, $< 4''$ at 7μm), as would be expected if it is predominantly a manifestation of the unresolved central radio source (c.f. Kellermann, Zensus, & Cohen 1997)). In the case of the $IRAS$ data, the best HIRES beams achieved in this paper are still fairly large ($50''$ to $90''$) so that the core extent is impossible to constrain and its flux density not easily separable from that of the extended emission. Therefore, the ellipse $IRAS$ flux densities listed in the table are simply the integrated measurements minus the core flux density of 8 ± 2 Jy, at both 100μm and 60μm, which is an extrapolation from the submm core SED ($\alpha_{81\,\mathrm{GHz}}^{877\,\mathrm{GHz}} = -0.01$, $S_\nu \propto \nu^\alpha$) to 60μm (5000 GHz). A full discussion of

the SED of the submm core in Centaurus A, and its implications, is outside the scope of this paper; for an extensive analysis of this matter, see, among many others, Bailey et al. (1986); Hawarden et al. (1993); Kellermann, Zensus, & Cohen (1997); Alexander et al. (1999); and Marconi et al. (2000).

The integrated submm to far-IR flux densities are fit by a two-component, optically-thin modified blackbody of the form

$$S_\nu = (1 - \exp(-\lambda_\mathrm{o}/\lambda)^\beta)[\Omega_1 B_\nu(T_1) + \Omega_2 B_\nu(T_2)], \tag{3}$$

where S_ν is the observed flux density at frequency ν, Ω the solid angle for the modified blackbody component, $B_\nu(T)$ the Planck function at temperature T, λ_o the wavelength at which the optical depth is unity and β the emissivity index of the grains. First, a 12 K and 40 K two-component modified blackbody with dust emissivity index of 1.3 fits the data for the $inner$ $disk$, and secondly, a 12 K and 30 K modified blackbody with dust emissivity index of 1.6 fits the data for the $outer$ $disk$ (c.f. Figure 6). These fits, in particular the derived relative emissivities and temperatures, are consistent with the spectral index maps, showing that the average dust temperature decreases from the galactic core outwards. Unsurprisingly, these temperatures are also consistent with the 42 K and 32 K determined by Eckart et al. (1990) from their 50 and 100μm $IRAS$ flux densities alone, as well as the average ~ 40 K determined by Unger et al. (2000) from their 40 to 100μm ISO LWS maps of the $inner$ $disk$ region.

The mass of emitting dust M_d can then be estimated from (e.g. Hildebrand 1983)

$$M_\mathrm{d} = \frac{S_\nu D^2}{k_\mathrm{d} B(\nu, T)}, \tag{4}$$

where S_ν is the measured flux density at frequency ν, D is the distance to the source, $B(\nu, T)$ the Planck function and $k_\mathrm{d} = 3Q_\nu/4a\rho$ the grain mass absorption coefficient where a and ρ are respectively the grain radius and density. Values of $k_\mathrm{d}^{450\,\mu m} = 0.25\,\mathrm{m^2 kg^{-1}}$ and $k_\mathrm{d}^{60\,\mu m} = 3.3\,\mathrm{m^2 kg^{-1}}$ (e.g. Hildebrand 1983) are assumed, yielding dust masses of $2.5 \times 10^4 \mathrm{M}_\odot$ for T = 40 K and $9.6 \times 10^5 \mathrm{M}_\odot$ for T = 12 K in the $inner$ $disk$ and dust masses of $4.9 \times 10^4 \mathrm{M}_\odot$ for T = 30 K and $1.2 \times 10^6 \mathrm{M}_\odot$ for T = 12 K in the $outer$ $disk$. The to-

tal mass for the dust that emits from the far-IR through the submm wavelength is then $9.9 \times 10^5 M_\odot$ and $1.2 \times 10^6 M_\odot$, respectively in the *inner disk* and *outer disk*, giving an overall total of $2.2 \times 10^6 M_\odot$ for the dust lane region of the galaxy we have observed (ie. radii $< 225''$ or $\sim 4.5\,\mathrm{kpc}$).

The advantage of using optically thin submm emission to determine the dust mass is, unfortunately, offset by the increased uncertainty in the properties of dust and subsequently of k_d, as λ is increased from the far-IR to submm wavelengths. A different choice of k_d could result in an estimation of the dust mass that differs by a factor as large as ~ 10 (Draine 1990). The dust mass derived in this paper in a region of radius $\sim 90''$ (the *inner disk*) is at the lower end of the dust mass of $1 - 2 \times 10^6 M_\odot$ derived by Block & Sauvage (2000) from their $V - 15\mu$m spatial distribution map in the same area. This is surprising because they reported the estimate was from dust in the "bar+arms of a mini-spiral, excluding any diffuse dust." However, given the uncertainty, the mass in this paper for the *inner disk* dust is at least *consistent* with Block & Sauvage (2000).

4. Conclusions

The SCUBA 850 and 450μm images in this paper show that the submm continuum morphology and spectral index distribution of Centaurus A comprise:

1. **The Nucleus** and associated structures: A distinct, unresolved, flat-spectrum AGN core with circumnuclear structure, including, to the northeast and southwest, areas of low spectral index which we suggest arise from free-free emission in ionised gas entrained in the nuclear outflow;

2. **Inner disk:** A prominent, elongated feature that may be a circumnuclear ring (or bar) extends across the center of the galaxy out to a radius of $\sim 90''$. It contains considerable real structure, including concentrations of emission towards its ends and a reverse-S-shaped twist; this structure appears reflected about the nucleus. The details of this structure are very similar indeed to what is seen on mid-IR *ISO* images, so the cooler dust seen in the sub-mm is very closely co-extensive with the much warmer material (transiently heated by UV-photon absorption) seen at 7 and $15\,\mu$m, and which establishes that the *inner disk* is a locus of vigorous star formation. It is also a strong source of CO emission with kinematics consistent with a ring or rings of gas around the nucleus, rather than a bar, as has been suggested elsewhere (Mirabel et al. 1999).

3. **Outer disk and outlying dust features:** Low-level emission, at least some of which comes from the foreground material in the prominent optical dust lane, extends to the eastern, and probably to the western, end of our maps. It traces the clockwise twist of the optical feature.

   Some of the observed low-level emission does *not* coincide with optically-visible dust. The sensitive SCUBA images are, for the first time, showing the direct detection of emission arising from dust that is in the far side of the galaxy, overlaid and obscured by the stellar component of NGC 5128, and thus not seen in optical images.

A warped disk model consisting of tilted rings (Quillen, Graham, & Frogel 1993) predicts the structure of the warmer and colder material, especially in the *inner disk*, rather well. It appears that in this vicinity the IR and submm images to a large extent reveal the same material; however, at larger radii, the dust is cooler because it is immersed in a much less intense stellar radiation field. Alternative arguments are presented in papers by Mirabel et al. (1999) and Block & Sauvage (2000), who interpret the mid-IR (and brighter submm) structures as a true barred spiral.

Using the continuum integrated flux densities from far-IR through submm wavelengths, this paper derives a total dust mass of $2.2 \times 10^6 M_\odot$ within a radius of $225''$ of the nucleus of Centaurus A. About 45% of the dust mass is in the star-forming *inner disk* within about $< 90''$ of the nucleus.

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Fig. 1.— Images of Centaurus A obtained with SCUBA at 850μm (top) and 450μm (bottom), derived from a series of individual "jiggle-mapping" (see text) exposures offset along a line roughly corresponding to the optical dust band of Centaurus A. The 450μm image is smoothed slightly and the central source displayed saturated in order to highlight the low-level, extended emission. The panel key indices are in Jy/beam corresponding to color-coded intensities, and the contour heights in the 850 and 450μm images are [0.01, 0.03, 0.05, 0.07, 0.1, 0.14, 0.2, 0.3, 0.4, 1.0, 2.5, and 4.0 Jy/beam] and [0.04, 0.16, 0.28, 0.40, 0.52, 0.8,1.0, 1.5, 2.5, and 3.5 Jy/beam] respectively.

Fig. 2.— Image of the central $4'$ at 850μm obtained using with SCUBA and using the complementary "scan-map" technique. The central source is displayed saturated in order to highlight the low-level, extended emission. This map covers a smaller area than the "jiggle-mapping" set in Figure 1. The

panel key indices are in Jy/beam corresponding to color-coded intensities, and the contour heights are [0.07, 0.1, 0.2, 0.4, 1.0, 2.5, and 4.0 Jy/beam].

Fig. 3.— Profiles of the emission from Centaurus A at 850 (top) and 450μm (bottom) along an axis roughly coincident with the optical dust lane. The profile of the JCMT beam is superimposed in a line marked with crosses. This beam profile is obtained from a map of the JCMT pointing source 3C 279 scaled to the peak flux of Centarus A and determined along an axis roughly coincident with the major axis of the dust lane.

Fig. 4.— Contours of the 450μm image (see Figure 1) superposed on, from top to bottom, (a) an optical waveband image of Centaurus A, digitised from the *IIIaJ* emulsion photographic plates which are sensitive to emission between 395 and 540 nm wavelengths, courtesy of the Anglo-Australian Observatory, and (b) a 7μm ISOCAM negative image (Mirabel et al. 1999). The contour heights of the 450μm emission in (a) and (b) are [0.04, 0.16, 0.28, 0.40, 0.52, 0.8, 1.0, 1.5, 2.5, and 3.5 Jy/beam.] and [0.4, 0.7, 0.96, 1.2, 2.4, and 4.8 Jy/beam], respectively. In (a), the contours are of the slightly smoothed image, presented as the 450μm map in Figure 1 to highlight the low surface brightness emission that corresponds with the outlying parts of extended optical dust lane.

Fig. 5.— Map of the spectral index distribution at submm wavelengths, derived from the 450 and 850μm data presented in this paper (see Figure 1). Four regions are clearly apparent in the map: the unresolved core (blue-black) and a feature apparently representing the inner jet (green-blue) in the nuclear area; and the bright, reverse-S-shaped *inner disk* (yellow-green-red), familiar from the intensity maps (shown in Figure 1), and the fainter

outer disk (red-yellow) farther from the nucleus. Contour heights at the spectral indices 2.0 (dashed lines) and 3.0 and 3.3 (solid lines) are overlayed to guide the eye to the the inner jet and inner disk features in the map. The panel key indices correspond to color-coded spectral indices obtained between 850 and 450μm.

Fig. 6.— Integrated flux densities in two annuli centered on the core of Centaurus A. The error bars indicate the uncertainty in the flux density measurements, which are dominated by the uncertainty in the flux calibration and to a lesser extent the beam error-lobe contribution. The top and bottom SEDs are respectively for the *inner disk* of $60 \times 180''$ minus the core flux density and the *outer disk* annulus of $120 - 60 \times 450 - 180''$. The submm to far-IR data points are fit by two component optically thin modified blackbodies of temperatures $12\,\text{K}$ and $40\,\text{K}$ with dust emissivity index of 1.3 for the *inner disk* (top) and $12\,\text{K}$ and $30\,\text{K}$ with dust emissivity index of 1.6 for the *outer disk* annulus (bottom).

Table 1: Submm to Mid-IR Fluxes of the Centaurus A Core and Extended Emission

Filter	Frequency (GHz)	Core[a] (Jy)	*Inner disk*[b] (Jy)	*Outer disk*[c] (Jy)
SCUBA 850[d]	350	8.1 ± 0.8	2.7 ± 0.4	3.4 ± 0.5
SCUBA 750[d]	407	8.1 ± 1.6	···	···
SCUBA 450[d]	667	7.9 ± 0.8	16.9 ± 3.2	22.6 ± 5.2
SCUBA 350[d]	866	7.7 ± 1.9	···	···
IRAS 100	3000	···	119 ± 20[e]	181 ± 36
IRAS 60	5000	···	96 ± 15[e]	77 ± 15
IRAS 25	12000	···	15 ± 2[f]	6 ± 1
ISOCAM 15	20000	1.2	10.4	···
IRAS 12	25000	···	11 ± 2[f]	6 ± 1
ISOCAM 7	42857	0.7	9.4	···

[a] Peak fluxes of the unresolved core, which in the case of the SCUBA and ISOCAM images was clearly distinct from the extended emission.

[b] The integrated fluxes determined in an ellipse of $60 \times 180''$ minus the core flux.

[c] The integrated fluxes determined in an elliptical annulus of $120 - 60 \times 450 - 180''$.

[d] The SCUBA filter bandwidths are all about 30 GHz.

[e] In the case of these 100 and 60 μm ellipse fluxes, the core fluxes subtracted off are an extrapolation of the submm core flat SED ($\alpha_{81\,\mathrm{GHz}}^{877\,\mathrm{GHz}} = -0.01$, $S_\nu \propto \nu^\alpha$) to 60 μm (5000 GHz), as the HIRES beams are very large ($50''$ to $90''$) so that it was impossible to isolate the core measurements from the extended emission.

[f] Core fluxes have not been subtracted from these integrated fluxes as no reasonable estimate of the core measurements at these wavelengths could be extrapolated from our present data.

NOTE.—The *IRAS* data were re-processed using HIRES routines at NASA/IPAC.

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